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Poly-generation as a solution to address the energy challenge of an aging population

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ABSTRACT

The increasing number of elderly people (over 65 years of age), long-term home care policies and the generally higher energy demand of houses inhabited by elderly people will pose an energy challenge for the built environment. The paper analyses the benefits of poly-generation technologies, focusing on the case of hard to heat homes in Northern Ireland. The energy consumption of a test house that is representative of 28% of Northern Ireland housing stock and of a house with elderly inhabitants has been monitored without any intervention. An optimization procedure has been developed to identify the optimal mix of poly-generation technologies. The technologies considered are micro-combined heat and power, heat pump and photovoltaic systems with possible integration of thermal energy storage systems. Six scenarios based on different energy tariffs and technology incentives have been presented. In the best case scenario, the combination of photovoltaic, heat pump and thermal energy storage provides 26% reduction in carbon dioxide emissions and 80% savings in the energy bill compared to standard energy generation. The investment required would be in the order of £11,000. In Northern Ireland, 307,000 households (79.1% more than in 2012) will have elderly inhabitants by 2037. The adoption of poly-generation technologies in the older housing stock could lead to 8% reduction of carbon dioxide emissions of the entire residential sector, with 150 GWh increase in the electricity generation from renewable energy without affecting the electricity distribution network.

KEYWORDS

Poly-generation, renewable energy, optimal technology mix, optimal sizing, heat pump, PV, thermal energy storage, cogeneration, elderly

Highlights

- The built environment is facing an energy challenge due to an aging population.
- Benefits of poly-generation for houses inhabited by elderly people were analysed.
- Results show 26% reduction in CO_2 emissions and 80% savings in the energy bill.
- Potential 8% reduction in CO_2 emissions of the national residential sector by 2037.

ABBREVIATIONS

CHP	Combined Heat and Power System
CO_2	Carbon dioxide
CO_2ER	CO_2 Emission Reduction
COP	Coefficient of Performance
ICE	Internal Combustion Engine
Micro-CHP	micro Combined Heat and Power
NPV	Net Present Value
PBP	Pay Back Period
PES	Primary Energy Savings
PV	Photovoltaic
RHI	Renewable Heat incentive
SPB	Simple Pay Back period
STC	Standard Test Condition
TES	Thermal Energy Storage
TOU	Time Of Use
US	United States of America
VAT	Value Added Tax

Symbols

A	Annualised
AC	Annualised Cost
amb	Ambient
boiler	boiler
buy	buy
C	Cost

C_0	Investment cost
c	*cost*
e	energy
EB	Energy Bill
EF	Emission Factor
El	electric
FiT	Feed in Tariff
fuel	fuel
grid	electricity grid
in	inlet
h	hour
HP	heat pump
lifespan	lifespan
k	day
O&M	operating and maintenance
op	operating
out	outlet
poly	poly-generation
PE	Primary Energy
r	interest rate
RHHP	Renewable Heat produced by the air source Heat Pump
S	Savings
sell	sell
SP	separate production
T	Temperature

th	thermal
unit	unit

1. INTRODUCTION

By the year 2050, one in five people worldwide will be over 65 years of age [1]. In the European Union (EU), currently elderly people (over 65 years of age) represent 18.5% of the population. The combination of a low birth rate and higher life expectancy is increasing the number of elderly people at a yearly rate of 0.3%, in line with the global prediction [2].

An aging population increases age related disease and, therefore healthcare costs. The time spent at home by elderly people will increase in the near future with the need to adapt houses to elderly needs. First, an increase in the time spent home is justified by social reasons. Living at home as much as possible improves the quality of life of elderly people. Keeping the same lifestyle and the social ties with family and friends can help the wellbeing of elderly people [3]. Second, the increase of the time spent home is justified by economic reasons, since the higher number of elderly people could not be handled by hospitals and current care homes. After an injury, elderly people are frequently prevented from going back home [4]. Making their living environment 'smart' would allow elderly people to go back home and live better [5].

Several countries have recently launched programs to promote long-term home care policies, helping elderly people to address the gradual deterioration of their abilities. In some municipalities of Sweden, elderly people can choose between receiving support to improve their homes or living in special housing provided by public or private operators [6].

The higher number of elderly people and long-term care policies, in addition to societal and economic challenges, will pose an energy challenge for the built environment, which is already responsible for 40% of carbon dioxide (CO_2) emissions [7]. Electricity consumption will increase due to a higher use of assisted living technologies that are able to enhance the independent living ability [8]. For example, the annual growth in the sale of home monitoring systems in the United Kingdom (UK) was 2.9% between 2011 and 2017 [9]. The major factors driving an increase in electricity demand are: i) longer running hours for appliances, due to more time spent at home and ii) "high consumers" attitude of the current generation, who will be the next elderly generation [10].

The elderly cohort is different where a high percentage live with low income, while the wealth gap is increasing with those better off. However, electricity consumption is expected to increase for both categories. Better off older people have, indeed, the financial means to be high electricity consumers. A low elasticity of the energy demand prevents lower income households to reduce the energy consumption. Moreover, elderly people with a low income are more likely to use old appliances, characterized by higher consumption and lifespan [11].

Age is recognized as one of the key demographic factors for thermal demand. Deutsch and Timpe [12] argued that elderly people spend from 70% to 90% more time at home, occupying larger and older houses with lower energy performances. The majority of elderly people are home-owners. In the UK, elderly people represent 73% of the home-owning population [12]. Elderly people are less willing to downsize and to move house, since they tend to be more attached to their house and neighbourhood, and since their income is generally low, elderly people are less willing to invest in new technologies [12].

Energy consumption is significantly different between younger and older generations. For example, in the United States of America (US), per capita space heating demand of people aged between 65 to 74 years of age was 8,059 kWh compared to 3,136 kWh for individuals aged between 33 to 44 years of age in 2001 [13]. The economic expenditure of people over 65 years of age is, on average, 110 euro per month per capita, about 45% higher than for people aged between 25 and 35 years of age [14].

Older and less energy efficient houses make to achieve thermal comfort conditions more difficult, increasing the risk of health and winter death. Equally in hotter climates and in urban heat islands, overheating has been a problem and deaths among the elderly population have been noted [15]. The present study will however focus on heating needs.

According to [16], the risk of death was higher during winter and for people living in energy inefficient homes. Since elderly people have lower income than younger adults and generally live in older houses, elderly people are more likely to suffer from fuel poverty [17]. Fuel poverty occurs when a household cannot be kept warm at a reasonable cost [18]. In England, in 2013, 1.14 million elderly lived in fuel poverty [16]. In the UK, 19% of the elderly are in poverty before and 17% are in poverty just after housing costs. In the US, the energy expenditure of low income elderly is 13% of their annual income [18].

There are three main drivers of fuel poverty: energy inefficient houses, high energy costs and low incomes. The percentage of people suffering from fuel poverty has decreased in recent years due to dedicated policies. Examples include: reduced energy tariffs for low income households and the former Green Deal, which encouraged homeowners to invest in energy efficiency [16]. Living in energy inefficient houses also affects the social wellbeing of elderly people as they may be reluctant to invite friends at home that leads to social isolation [19]. The result suggests that investigating energy efficient solutions to address the energy challenge of an aging population could have a positive impact on society.

1.2 PROBLEM STATEMENT

An increase in the energy demand of houses inhabited by elderly people poses a double challenge: higher CO_2 emissions of the built environment and elderly people at risk of not being able to pay their energy bills. In recent years, several studies and international projects have focused on new "green and grey buildings" [20]. Green and grey buildings are defined as buildings that follow green building standards and consider the needs of elderly people.

Weberhause [21], for example, is a German company that specializes in the design of prefabricated green buildings equipped with smart technologies. The 700 series CityLife house follows green building standards. Due to highly insulated windows and walls and the introduction of heat recovery technologies, the energy consumption of the CityLife House meets the requirements of a passive house. A passive house has a thermal demand lower than 15 kWh per square meter, which is 77% lower than standard houses [22]. The energy for all domestic applications, furthermore, does not exceed 60 kWh per square meter of treated floor area per year. However, although there are several studies about green and grey buildings, only few studies have looked at existing accommodations, in particular high energy consuming accommodations inhabited by elderly people. Yamasaki and Tominaga [10] made a detailed analysis of the residential demand of elderly people (aged over 65) in Japan and showed their high per-capita energy intensity. Hamza and Gilroy [23] analysed the energy demand of elderly people in the UK showing how a cohort of "high consumer" elderly people could affect the likelihood to meet national climate targets. However, there has been insufficient investigation to reduce energy consumption for elderly people in the UK. The work aims at studying whether and when investing in poly-generation technologies could be cost effective for retrofitting households inhabited by elderly people.

Poly-generation, also known as hybrid energy generation, describes the combined production of multiple energy products [24]. Poly-generation technologies may use a wide range of fossil and renewable energy sources to take advantage of different energy conversion technologies and produce a range of products, such as heat and electricity [25]. Poly-generation systems in buildings are used with the aim of reducing fuel consumption, operating costs and CO_2 emissions with respect to standard energy generation [26], whereby the electricity is bought from the grid and boilers are used to satisfy the thermal need.

However, there is not one single lay-out and a perfect mix of technologies. For example, Al-Sharafi et al. [27] looked at the use of Photovoltaic (PV) array, wind-turbine, battery bank and diesel engine to satisfy the energy demand of a building in Kingdom of Saudi Arabia. Ma et al. [28] analysed the benefits of combined cooling heat and power systems, along with a PV and ground source heat pump (HP) integration. Nevertheless, the optimal design of poly-generation technologies is the key for the uptake of the solution [29], due to the high investment cost of technologies and the high number of parameters that influence the economic and energy savings, such as technology constraints, energy tariffs and variability of thermal and electrical demand.

The present work focuses on the optimal mix of poly-generation technologies to meet the energy demand of households inhabited by elderly people at the minimum total cost (capital and operating). The motivation for this paper arises from the fact that there are: i) limited studies on low carbon solutions for houses inhabited by elderly people in the UK and the EU, ii) limited investigation on hard to heat homes typically, in retrofit conditions where a high temperature (above 65°C) HP is used and iii) limited information on integrated system optimization to match energy demand of hard to heat homes.

Thus there is a need to add to the limited body of literature in this area and the case study is representative of a significant number of homes within the UK housing stock. There is a strong correlation between hard to heat homes and energy consumption of houses inhabited by elderly people. Optimal size and management of poly-generation technologies for CO_2 emissions and cost reduction is a possible solution. The work aims to provide a rational for combining social and energy policies. The present paper investigates whether the use of poly-generation technologies in houses inhabited by elderly people could help to: i) reduce the housing cost for energy, ii) address the fuel poverty, making a long-term home care policy more affordable and ii) address climate challenge compliance within the building sector. The optimal sizing and management method developed has also been used to understand behind the meter strategies for houses inhabited by elderly people. The idea is to investigate if the optimal integration and management of low carbon technologies may help electricity network operators to postpone network investments to accommodate variable renewable energy and increase the percentage of renewable sources in the national energy supply. The work does not simply focus on the specific case analysed. A sensitivity analysis has been developed in order to consider the variation of the main design parameters, such as the variation of the electrical and thermal loads that is derived by considering different geographical locations.

The analysis is based on the energy demand of a test house from Northern Ireland. It is a terraced street house built according to year 1900 standards and used for testing retrofit technologies in a real environment. The test house is a hard to heat home and represents about 28% of the housing stock in Northern Ireland [30]. Different energy conversion technologies in the poly-generation system are simulated: micro-Combined Heat and Power (micro-CHP), PV, HP systems and thermal energy storage (TES) technologies. Technologies have been selected considering: i) local availability of renewable sources, ii) thermal comfort criteria, iii) minimum investment and operating cost and iv) minimal intervention and education for elderly people.

In addition to the literature review and the problem statement, the paper is structured in three sections. Section two discusses the method with particular regard to the optimisation model developed and the case study. Section three shows the results gained, followed by discussion and conclusion.

2 METHOD

The scientific literature argues that optimal design of poly-generation units can help to maximize economic and energy savings [31]. This is a key aspect for identifying the proper investment in poly-generation technologies to reduce the environmental impact of an increasing energy demand and provide cost effective solutions for households inhabited by elderly people and those threatened by fuel poverty. When dealing with poly-generation systems, identifying the optimal mix of technology is a tough issue due to several parameters that must be taken into account in the analysis. Several techniques could be used to solve the optimization problem. Examples are: i) maximum rectangle method [32], ii) linear programming [33], iii) mixed integer linear programming, iv) fuzzy logic and v) genetic algorithms [34] that are generally combined with multi-objective optimization [35].

The present paper addresses the optimal sizing and management of poly-generation systems defined on the basis of linear programming techniques, taking advantage of rapid calculations even in the presence of a high number of variables.

An optimisation algorithm based on linear programming has, therefore, been developed and used in the analysis. Five parameters have been considered in the analysis: i) energy tariffs, ii) ambient conditions, iii) energy demand, iv) technologies and v) grid constraints.

As mentioned earlier, the analysis has been based on a test house in Northern Ireland, whose energy demand has been monitored for an entire year. Detailed information about the case study is provided in section 2.3.

2.1 Modelling of energy conversion technologies

Different retrofit technologies have been considered and modelled on the basis of their main performance parameters: micro-combined heat and power, HPs, PV units and TES. The technologies and the optimization model have been developed in MATLAB environment. As previously stated, poly-generation technologies have been chosen considering local availability of renewable sources, thermal comfort criteria, minimum investment and operating cost, minimal intervention and education for elderly people. Micro-CHP technologies are energy saving solutions, which can be fuelled both by natural gas or biomass and lead up to 25% of primary energy savings compared to standard energy generation [36]. Micro-CHP generation refers to the simultaneous production of electricity and heat with electricity production lower than 50 kW_{el}. For such a reason, micro-CHP units can provide higher savings in cold climates characterised by a higher heat demand along the year and, therefore, by a lower seasonal variation of the heat to power ratio [37]. The technology simulated in the model is an internal combustion engine (ICE), which is the most mature and cost effective, due to its higher electrical efficiency and reliability. The ICE has been modelled on the basis of its electrical and thermal efficiency considering the design parameters of a commercial unit [38], whose main characteristics are shown in Table 1.

PV systems are particularly suitable for building and retrofit applications. The investment cost of PV systems has been strongly reduced over the past years in the UK due to government supporting policies. Moreover, solar irradiation shows a very good correlation with domestic electricity load profiles. The model described in [33] has been used to assess the PV power production per kW installed, providing the input to the optimisation model used in the present analysis. The efficiency of the PV panel has been defined as a function of the ambient conditions, in particular of the solar radiation and the solar cell temperature. TRNSYS has been used to calculate the solar radiation [39]. The value of the global and tilted solar radiation has been defined by considering a tilt angle of 32 degrees, that allows to achieve the maximum electricity production for the specific location. TRNSYS uses a typical meteorological year based on the information provided by a meteorological station in Belfast and generated using Meteonorm under the license from Meteotest [40].

The reference PV panel is a commercial polycrystalline module manufactured by Sharp. It has an effective aperture area of 1.47 m^2 and its nominal cell efficiency and its performance parameters are used in the model to evaluate the module performance under real working conditions. In Standard Test Conditions (STC), the efficiency of this module is 14.6%, its peak power production is 240 W and the efficiency temperature coefficient is 0.0044 $°C^{-1}$ [41].

A pump in domestic applications works well up to 55°C to provide space heating through under floor heating and with new/smart radiators. In contrast, for a conventional HP, the performance drops as flow temperature increases. However, HP installation as a retrofit technology requires minimum changes to existing control and radiators. In addition, a HP needs to work at a high flow temperature (around 76°C same as a gas boiler) when coupled with a conventional radiator system in retrofit installation. For this purpose, a cascade air-source HP with 11 kW capacity has been studied as retrofit installation in terraced street houses, which can provide flow temperature up to 80°C. The HP flow temperature was set at 76°C and it provided both space heating (using conventional radiators) and hot water demand for the house (see section 3.2). HP performance was monitored for over a one-year period in different configurations, such as direct mode, storage mode and combined mode [42]. The simulation model for HP considers two parameters: coefficient of performance (COP) and outdoor ambient temperature (T_{amb}) whereas flow temperature is kept constant.

Table 1 shows the parameters used in the HP simulation model, where an equation has been derived for HP COP with respect to outdoor ambient temperature based on actual cascade HP experimental data. The ambient temperature provided by TRNSYS has been used by the optimization algorithm described in section 2.2 to take into account the variation of the COP of the HP.

TES systems have also been considered in the analysis. TES systems provide the opportunity to store thermal energy by heating a storage medium; therefore, energy can be used at a later time. TES systems are particularly suitable for buildings where a significant share of the user demand is in the form of thermal energy, with sudden and steep variations during the days and from one day to another. Therefore, if properly managed, TES systems could contribute to reduce energy consumption, emissions and system costs. At present, it is possible to mention three typologies of TES systems: i) sensible heat storage, based on heating a liquid or solid storage medium, since water is the easiest and most common solution, ii) latent heat storage by adopting phase change materials and iii) thermo-chemical storage by using chemical reactions to store thermal energy. Among the aforementioned solutions, sensible heat storage is the most mature and currently, the most practical and affordable technology. Sensible energy storage can be easily embedded in domestic systems. The model simulates sensible heat storage with water. An efficiency of 90% and an investment cost of 3.2 £/litre have been assumed in the analysis [43].

Table 1. Poly-generation technologies under analysis

Technology specification	**Techno-economic values**
	Micro-CHP unit [38]
Electrical efficiency	30%
Heat to power ratio	1.7
Investment cost [£/kW]	3,010 £/kW
Lifespan	48,000 hours
	PV Module [41]
Cell Type	Polycrystalline silicon solar cell
Module model	Sharp ND-R240A6

Module power (STC)	240 W
Module electrical efficiency (STC)	14.6 %
Module temperature coefficient	0.0044 °C^{-1}
Investment cost [£/kW]	1,400 £/kW
Lifespan	20 years
HP unit	
Hot water flow temperature	75 °C
COP	$0.09 \cdot T_{amb}+1.88$ [42]
Investment cost [£/kW]	800 £/kW [44]
Lifespan	15 years [44]
Thermal energy storage [43]	
Efficiency[b]	90%
Difference in water outlet inlet temperature	15 degree Celsius
Investment cost [£/Litre]	3.2 £/Litre
Lifespan	15 years

[b]*The efficiency of the TES, also defined as the first-law efficiency is given by the ratio between the energy extracted from the heat storage to the energy stored in it [45].*

2.2 Optimisation algorithm for techno-economic and environmental analysis

The optimization model selects the typology and size of poly-generation technologies to satisfy the final energy demand of households inhabited by elderly people, with the aim of minimizing the total annual cost of energy. Poly-generation technologies are assumed to be coupled to an existing gas boiler, whose capital cost is, therefore, not considered. Poly-generation technologies are selected by the model only if the sum of the annualised capital cost plus the operating cost of the resulting energy system is lower than the operating cost for standard energy generation (defined in the present work as separate production in contrast with the combined production of heat and electricity).

Figure 1 shows the lay-out of the poly-generation system considered in the analysis and whose rational has been explained in section 1.2. Potentially, electricity can be bought from the electricity network or produced by PV or micro-CHP units. Thermal demand can be satisfied by the: i) heating boiler, ii) micro-CHP, iii) HP or iv) the TES fed by micro-CHP and/or HP. The air-to-water HP considered in the analysis can be fed by the electricity generated by the national electricity network or by the PV unit. A 3.4 kW cap on the maximum electrical output of the PV unit has been considered in the model, constrained by the roof space availability of the test house under analysis.

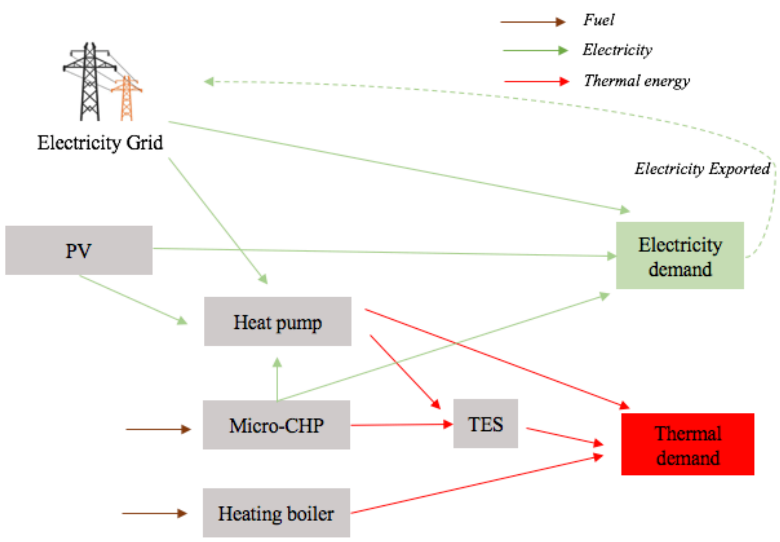

Figure 1. Lay-out of the poly-generation system under analysis

The criterion adopted for the objective function is the minimisation of the total annual energy cost. The energy and economic benefits of a poly-generation system is assessed against standard energy generation. Eq. 1 shows the objective function used in the present work. The total annual energy cost (C^A) is given by the annualised capital cost (C^A_{AC}), summed to the yearly cost to operate the poly-generation system, C_{op}.

$$minC^A = C^A_{AC} + C_{op} = C^A_{micro-CHP} + C^A_{PV} + C^A_{TES} + C^A_{HP} + C_{op},$$

(1)

where C_{AC}^{A} is formed considering the annualised capital cost of each technology: $C_{micro-CHP}^{A}, C_{PV}^{A}, C_{TES}^{A}$ and C_{HP}^{A}.

The annualized capital cost of each technology, C_{AC}^{A} (Eq. 2) has been calculated on the basis of the capital cost of the technology, $C_{\mathrm{technology}}^{A}$, and the capacity recovery factor, considering an interest rate, *r*, of 3% and the lifespan of each unit shown in Table 1.

$$C_{AC}^{A} = \frac{C_{\mathrm{technology}}^{A} \cdot \mathrm{r} \cdot (1+r)^{lifespan}}{(1+r)^{lifespan} - 1} \tag{2}$$

The value of the annualised capital cost of the technologies under analysis is shown in Table 2. A typical day for each month has been considered in the analysis and results have been extended for the entire year. The yearly cost to operate the poly-generation system, C_{op}, is shown in Eq. 3. The cost is expressed in pound.

$$C_{op} = \sum_{k=1}^{12}\sum_{h=1}^{24} \begin{gathered} \left(c_{el}^{buy}\right)_{h,k} \cdot \left(e_{el}^{buy}\right)_{h,k} + \left(c_{fuel}^{boiler}\right)_{h,k} \cdot \left(e_{fuel}^{boiler}\right)_{h,k} + \left(c_{fuel}^{micro-CHP}\right)_{h,k} \cdot \left(e_{fuel}^{micro-CHP}\right)_{h,k} + \\ \left(c_{O\&M}^{micro-CHP}\right)_{h,k} \cdot \left(e_{el}^{micro-CHP}\right)_{h,k} + \left(c_{el}^{buy}\right)_{h,k} \cdot \left(e_{el}^{HP}\right)_{h,k} - \left(c_{\mathrm{el}}^{\mathrm{sell}}\right)_{h,k} \cdot \left(e_{el}^{\mathrm{sell}}\right)_{h,k} - \\ (FiT_{PV})_{h,k} \cdot (e_{el}^{PV})_{h,k} - (FiT_{RHI})_{h,k} \cdot (e_{th}^{HP})_{h,k} \cdot \left(1 - COP_{h,k}^{HP}\right) - (FiT_{micro-CHP})_{h,k} \cdot \left(e_{el}^{micro-CHP}\right)_{h,k} \end{gathered} \tag{3}$$

The total annual cost of energy is given by the sum of the costs minus the revenues. Cost are based on the following: i) electricity bought from the grid, e_{el}^{buy}, at the electricity tariff, c_{el}^{buy}; ii) energy associated with the fuel feeding the boiler, e_{fuel}^{boiler}, at the natural gas tariff, c_{fuel}^{boiler}; iii) energy associated with the fuel feeding the micro-CHP unit, $e_{fuel}^{micro-CHP}$, at the natural gas tariff, $c_{fuel}^{micro-CHP}$; iv) operating and maintenance of the micro-CHP unit, $c_{O\&M}^{micro-CHP}$, which is a function of the electric energy produced by the unit, $e_{el}^{micro-CHP}$, and v) electricity for feeding the HP, e_{el}^{HP} at c_{el}^{buy}. The revenues arise from the excess electricity sold to the grid, e_{el}^{sell}, at the export tariff, c_{el}^{sell}, and, for some scenarios, the revenues from government supporting mechanisms for poly-generation technologies. Incentives taken into account in the present paper are: Feed in Tariff (FiT) for PV production, which is common to several EU countries, renewable heat incentive (RHI) and FiT for micro-CHP generation. All these supporting mechanisms have recently run out for new installations in Northern Ireland, but are still available in Scotland, England and Wales, and are common to other EU countries, such as Italy and Germany [46]. In detail, the revenue from the PV incentive is given by a FiT, FiT_{PV}, multiplied by the electricity produced by the PV unit, e_{el}^{PV}. The revenue from the RHI is given by two parts: i) a grant of £1,700 towards the investment costs and ii) a FiT, FiT_{RHI}, for the renewable heat produced by the air source HP. The value of the renewable heat produced by the air source HP *(RHHP)* is shown in Eq. 4:

$$RHHP = e_{th}^{HP}(1 - COP) \tag{4}$$

where the *COP* is the seasonal performance coefficient of the HP. The seasonal performance coefficient in the objective function has been calculated by considering the variation of the coefficient of performance along the year, $COP_{h,k}^{HP}$.

The revenue from the micro-CHP incentive is given by a FiT for micro-generation technologies with a power output lower than 2 kW, $FiT_{micro-CHP}$ multiplied by $e_{el}^{micro-CHP}$.

The model includes three main constraints. Firstly, the electrical and thermal energy produced by the poly-generation system has to be equal to the electrical and thermal demand. Secondly, the energy output of each generation unit cannot exceed its maximum rating. Thirdly, the total amount of the heat stored at the beginning of each time step, after the second time step, is equal to the non-dissipated heat stored in the previous time step $\left(e_{th,TES}\right)_{h-1}$, plus the heat sent to the storage device in that time step $\left(e_{th,TES,in}\right)_h$, minus the heat released to meet the heat demand $\left(e_{th,TES,out}\right)_h$ (Eq.5).

$$\forall h,\ \left(e_{th,TES}\right)_h = \left(e_{th,TES}\right)_{h-1} + \left(e_{th,TES,in}\right)_h - \left(e_{th,TES,out}\right)_h \tag{5}$$

Table 2 shows the main economic parameters used in the simulations. Two are the electricity tariffs considered: a 0.148 £/kWh fixed electricity tariff, and a Time Of Use (TOU) tariff, known as economy 7 tariff, which charges a cheaper electricity price during off peak hours (1 a.m. to 7 a.m.).

The profitability of the poly-generation system is assessed using classic capital budgeting indexes, such as Simple Pay Bay period (SPB) (Eq.6), Net Present Value (NPV) (Eq.8), and Pay Back Period (PBP) (Eq. 9) [36].

The SPB is given by:

$$SPB = \frac{C_0}{S} \tag{6}$$

where C_0 is the initial investment in the poly-generation system and S represents the savings.

S (Eq.7) is given by the difference between the energy bill in case of separate production (EB_{SP}) and the Energy bill in case of poly-generation (EB_{poly}).

$$S = EB_{SP} - EB_{poly} \tag{7}$$

The NPV (Eq.8) is given by:

$$NPV = -C_0 + \sum_{k=1}^{n} \frac{S_k}{(1+r)^k} \tag{8}$$

where S_k represents the net savings at the year k calculated considering a discount rate r, equal to 3% and n is the project lifespan (Table 1). It is assumed that the investor finances C_0 with his/her own capital.

The PBP (Eq. 9) is the number of years in which C_0, is equal to the actualized value of the cash flow

$$-C_0 = \sum_{k=1}^{PBP} \frac{S_k}{(1+r)^k} \tag{9}$$

The energy and CO_2 emissions reduction achievable is based on the calculation of two indexes, the primary energy saving (PES) index (Eq.10) and the carbon dioxide emission reduction (CO_2ER) index, (Eq.11):

$$PES = 1 - \frac{e_{grid,poly} \cdot PE_{el} + e_{fuel,poly} \cdot PE_{fuel}}{e_{grid,SP} \cdot PE_{el} + e_{fuel,SP} \cdot PE_{fuel}}, \tag{10}$$

where $e_{grid,poly}$ is the electricity used by the poly-generation system, PE_{el} is the primary conversion factor for electricity, $e_{fuel,poly}$ is the energy associated with fuel used by the poly-generation system, PE_{fuel} is the primary conversion factor for the fuel used, $e_{grid,SP}$ is the electricity used by the standard energy generation and $e_{fuel,SP}$ is the energy associated with the fuel used by the separate production.

$$CO_2ER = 1 - \frac{e_{grid,poly} \cdot EF_{el} + e_{fuel,poly} \cdot EF_{fuel}}{e_{grid,SP} \cdot EF_{el} + e_{fuel,SP} \cdot EF_{fuel}}, \tag{11}$$

where EF_{el} is the emission factor for electricity, EF_{fuel} is the emission factor for the fuel used and $E_{fuel,SP}$ is the emission factor for the fuel used by the standard energy generation.

Table 2. Main techno-economic parameters considered in the analysis

Parameters	Values	Parameters	Values
c_{el}^{buy} [£/kWh]	0.148 fixed tariff [47] 0.1531TOU 7.00 a.m. - 1 a.m. 0.0746 TOU 1.a.m. – 7 a.m.	$c_{fuel}^{micro-CHP}$ [£/kWh]	0.048 [44]
c_{el}^{sell} [£/kWh]	0.041 [48]	c_{fuel}^{boiler} [£/kWh]	0.048 [47]
FiT_{PV} [£/kWh]	0.16244 [48]	$c_{O\&M}^{micro-CHP}$ [£/kWh]	0.018 [33]
$FiT_{micro-CHP}$[£/kWh]	0.0825 [49]	FiT_{RHI} [£/kWh]	0.037 [49]
C_{unit}^{A}	ICE: 353 [£/kW]	PE_{grid} [kWh PE/kWh]	2.5 [50]
	PV:94 [£/kW]	PE_{fuel} [kWh PE/kWh]	1.1 [50]
	TES:15 [£/kWh]	EF_{grid} [g/kWh]	520 [51]
	HP: 67 [£/kW] (54 with incentive)	EF_{fuel} [g/kWh]	235 [51]

The optimization procedure has been used to assess the optimal mix and size of poly-generation technologies for a house with elderly inhabitants, whose energy consumption have been defined in section 2.3. Six scenarios have been considered on the basis of different electricity costs and different incentives for microgeneration technologies (Table 3).

The six scenarios considered are: i) a fixed rate electricity tariff of 0.148 £/kWh and no supporting mechanisms for poly-generation technologies; ii) a TOU tariff for electricity and no supporting mechanisms, iii) a fixed rate electricity tariff with PV incentive, iv) a fixed rate electricity tariff with PV and RHI, v) a fixed rate electricity tariff with PV, renewable heat and micro-CHP incentives and vi) a TOU electricity tariff with PV, renewable heat and micro-CHP incentives. The value of the FiT and grants towards the investment cost considered for the supporting mechanisms are the ones currently available in Northern Ireland for installations completed before February 2016 [49].

Table 3. Scenarios analysed in the simulation

Scenario analysed	***Assumptions***		
N^o	***Natural gas tariff***	***Electricity tariff***	***Incentives***
1	*Fixed*	*Fixed*	*None*
2	*Fixed*	*TOU Tariff*	*None*
3	*Fixed*	*Fixed*	*PV incentive*
4	*Fixed*	*Fixed*	*PV and RHI*
5	*Fixed*	*Fixed*	*PV, RHI and micro-CHP*
6	*Fixed*	*TOU Tariff*	*PV, RHI and micro-CHP*

2.3 Case study

The case study is focussed on one of the two terraced street houses located at Ulster University and built according to year 1900 standards. The test houses have single solid walls where current energy efficiency measures are double glazed windows/doors and a minimum of 150 mm loft insulation. Figure 2 shows the mid-terraced type houses at Ulster University (house 63 and 64) where on either side of houses guard chamber is prepared, which maintains standard temperature in order to create a mid-terraced environment. During the monitoring, both houses were heated by a 21 kW_{th} gas boiler equipped central heating system. The reference scenario against which all the retrofit technologies will be analysed consists, therefore, in meeting the heating demand with a 21 kW_{th} gas boiler and buying electricity from the grid. Thermal and electrical energy demand for both houses were monitored for one year without any intervention or disturbance to occupants.

Figure 2. Terraced street test houses at Ulster University

Heat demand was obtained by heat meter, pulse output from gas meter and monthly gas bills, where gas boiler efficiency was measured at 80% (average). The gas meter error is of ± 2%. Electricity consumption of both houses was monitored using meter with pulse output. Electricity meter error is of ±0.2%. Data were logged 24 hours for 7 days in two schedules where schedule one runs every 15 seconds whereas schedule two runs every 1 minute. All data were logged by a data acquisition system and stored in a dedicated personal computer and cloud file storage for data analysis purposes.

Both houses have different occupancy levels in order to obtain an understanding of thermal/electrical energy demand. House 63 is occupied by a two-member family (working professional) where family members tend to go out in the morning and return in the evening. Three adults live in house 64 where one adult was with medical conditions during the field trial and spent most of the time at home whereas other two adults are university students who spent most of the time at home after University or during their break. The average daily occupancy level of house 64 is 15 hours, in line with the time spent by elderly people [12]. Energy consumption of house 64 has been therefore considered as representative of houses inhabited by elderly people and used in the simulation analysis. A comparison of the energy consumption of house 63 and 64, is reported in section 3.1, helping the reader to have a better understanding of the problem coming from high energy demands of an aging population.

3 RESULTS

The following sections show the results coming from the measurement of the energy demand of the two test houses described in section 2.3 and the optimal mix of technologies for the house taken to represent elderly inhabitants.

3.1 Measured energy consumption of the case study

The annual measured electricity consumption (Figure 4) of house 64 is about 4,600 kWh, 60% higher than house 63 (about 1,800 kWh/year). If those values of electricity consumption are compared with the average typical electricity consumption of domestic unrestricted consumers (profile class 1) in Great Britain [52], then house 63 falls in the "low consumption" range (lower or equal to 1,900 kWh per year), while house 64 is in the "medium consumption" range (between 3,100 and 4,600 kWh per year).

The typical domestic consumption values in Great Britain are defined by Ofgem, the Office of Gas and Electricity Markets, that is the government regulator for the electricity and downstream natural gas markets. Every year, on the basis of real data, Ofgem defines the typical energy consumer profile based on the two most recent yearly data.

Figure 3 shows the annual thermal energy demand comparison for both houses with the indication of the error (± 2%). It is clearly evident that the house (house 64) with higher occupancy (representative of a household with elderly inhabitants) requires more thermal energy in order to meet thermal comfort conditions. The total annual measured thermal demand for house 63 is 20,043 kWh and 26,188 kWh for house 64. Comparing the values with the typical domestic consumption value in Great Britain provided by Ofgem [52], which is of 17,000 kWh per year for the high consumer profile, the value measured is higher due to the characteristics of the houses under analysis and the worst climatic condition of Northern Ireland compared to other areas of the UK.

Figure 4 shows the monthly electrical demand of houses 63 and 64. The value of the error can not be visualised in the graph with ± 0.2%. Figures 5 and 6 show hourly variation in thermal and electrical energy demand in both houses. Energy demands are condensed in morning and evening times for house 63 (professional/couple occupied houses), whereas energy demands are scattered all around the day for house 64 (elderly/people with medical conditions). House 64 is taken to be representative of the energy consumption of elderly people and therefore used for assessing the benefits coming from introducing poly-generation technology. A typical day per month was used in the simulation, as discussed in section 2.2.

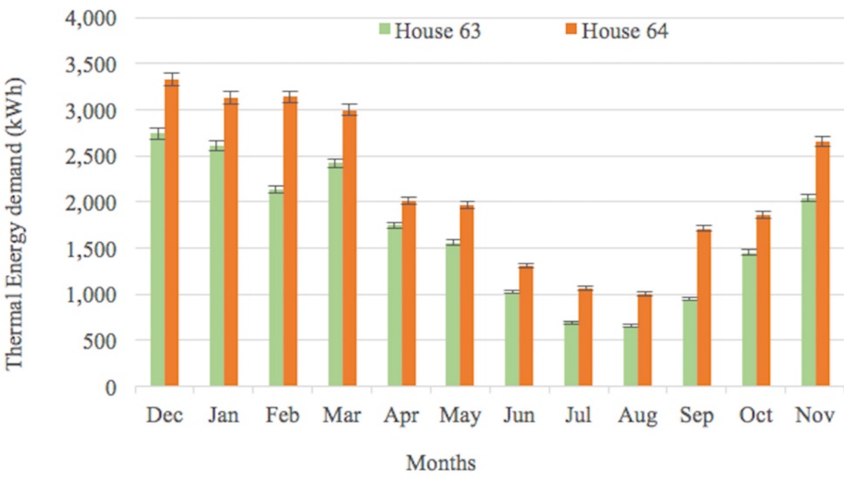

Figure 3. Measured annual thermal energy demand of terraced street houses

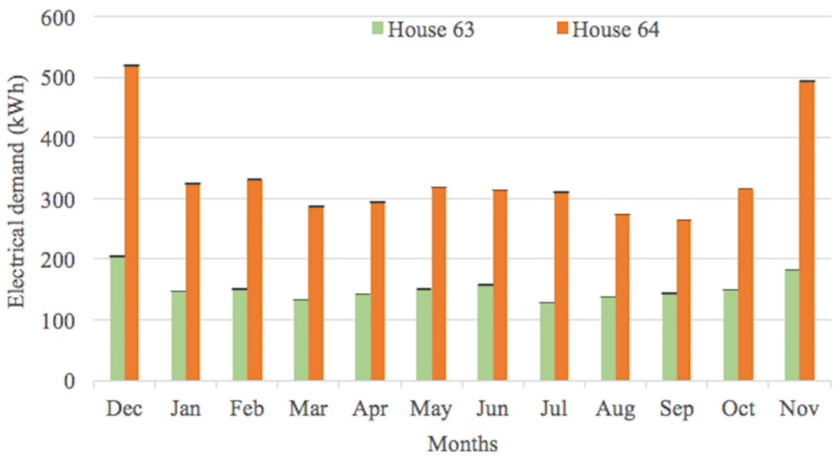

Figure 4. Measured annual electrical demand of terraced street houses

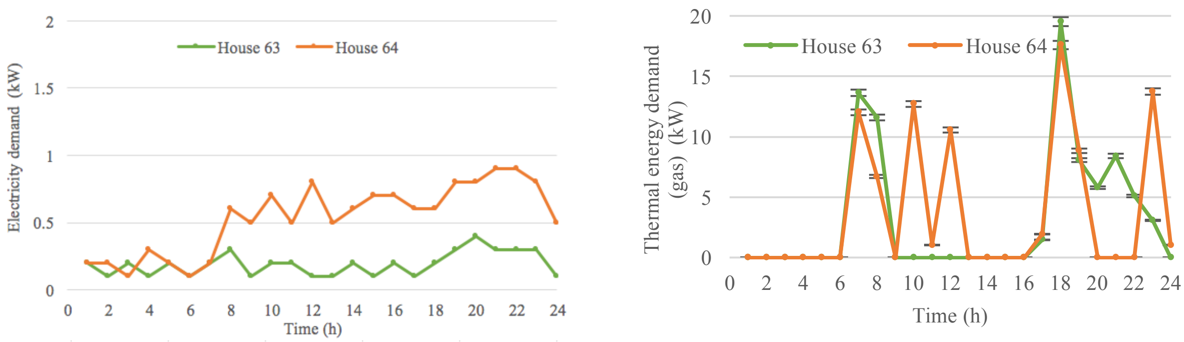

Figure 5. Measured electrical energy hourly profile for terraced street houses

Figure 6. Measured thermal energy (gas) demand hourly profile for terraced street houses

3.2 Simulation results

Using the linear modelling described in section 2.2 and on the basis of the energy demand of house 64, six different scenarios have been assessed (Table 3).

Table 4 shows the main output parameters for the analysed scenarios. The first four lines of Table 4 show the optimal sizes of the poly-generation technologies (micro-CHP, PV, TES and HP) selected by the model in order to minimise the annualised cost of energy that is defined by the value of the objective function that is shown in line 6. Table 4 reports the electricity exported to the grid that is expressed in kWh and as a percentage of the electricity produced by the electricity generation technologies (PV and micro-CHP systems). The PES index and the CO_2ER index reported have been defined according to Eqs. 10 and 11. The cost of the energy bill in case of separate production and with poly-generation technologies and the value of the economic savings are defined as a percentage reduction of the energy bill for separate production. Additional parameters shown in Table 4 are the investment in poly-generation technologies, SPB (Eq. 6), NPV over a 15-year period (Eq. 8) and PBP (Eq.9) that has been calculated considering an interest rate of 3%.

Table 4. Simulations results

Scenario	***1***	***2***	***3***	***4***	***5***	***6***
Description	*Fixed tariffs, no incentives*	*TOU electricity tariff, no incentives*	*PV incentive*	*PV and RHI incentives*	*PV, RHI and micro-CHP incentives*	*All incentives, TOU electricity tariff*
micro-CHP, ICE (kW)	0	0	0	0	0.8	0
PV (kW)	0	0	3.4	3.4	3.4	3.4
TES (kWh)	0	6.1	0	9.1	12	13.9
HP (kW)	0	2.2	0	3.3	2.5	4.5

Electricity exported to the grid (kWh,%[c])	0	-	(806) 47%	(30) 2%	106 (2%)	0
Objective function	£2,085	£1832.9	£1,867.8	£1,688.4	£1,412.3	£1,102.2
PES	0	9%	10%	23%	28%	25%
CO_2ER	0	9%	10%	24%	28%	26%
Bill Standard generation	£2,085	£1,835	£2,085	£2,085	£2,085	£1,835
Bill Poly-generation	-	£1,545	£1,640	£1,108	£481.87	£360.89
Economic Savings	0	15%	21%	47%	77%	80%
Investment	-	£2,872	£4,760	£9,039	£11,442	£10,913
SPB	-	~10 years	~11 years	~9 years	~7 years	~ 7 years
NPV over 15 year period	-	£880	£997	£3,601	£9,299	£8,158
PBP	-	~11 years	~12 years	~10 years	~7 years	~8 years

[c]*Percentage of electricity exported to the grid over the total electricity produced by poly-generation technologies*

4. DISCUSSION

Following the minimization of the total annual energy cost, poly-generation technologies are not selected without government supporting mechanisms. It means that standard energy generation is the best option to satisfy the thermal and electrical demand at the current electricity and natural gas tariffs.

In Northern Ireland, as in other countries like Italy and Germany, end-users can choose a TOU electricity tariff. In the UK, this tariff is known as economy 7 tariff. Prices are lower during off peak hours (1 a.m.-7 a.m). In this second scenario, the model selects a 2.2 kW HP combined to a 6.1 kWh TES (~350 litres with a difference in the TES water outlet and inlet temperature of 15 degree Celsius). However, the energy and environmental savings are limited (9%) as well as savings in the energy bill (15%). Furthermore, the size of the HP identified by the model is not commercially available.

The third scenario takes into account the PV incentive, which is common to several EU countries, such as Italy, Germany, Wales, Scotland and England [46], especially for small domestic applications. As shown in Table 3, the power output of the PV unit proposed by the optimisation model is capped by the roof space availability to 3.4 kW. The PES index is 10%, with 21% savings in the energy bill. In this case, the electricity sold to the grid is 47% of the electricity produced by the PV unit (about 806 kWh per year) with a potential stress on the electricity distribution network. The fourth scenario considers a RHI, which is currently available in some EU countries (e.g. Italy, Germany, Scotland and England [46]). In this case, the model selects a 3.4 kW PV unit, combined to a 3.3 kW HP and a TES with a maximum energy capacity of 9.1 kWh (~520 litres with a difference in the TES water outlet and inlet temperature of 15 degree Celsius). The energy and economic savings increase up to 23% and 47%, respectively, compared to standard energy generation. The electricity exported to the grid reduces to 2% (~ 30 kWh per year). The fifth scenario analysed considers all possible incentives for poly-generation technologies. In this case, the optimization model selects a 0.8 kW ICE and 3.4 kW PV system, a 2.5 kW HP coupled to a 12 kWh TES (~688 litres with a difference in the TES water outlet and inlet temperature of 15 degree Celsius). The PES, CO_2ER indexes and the reduction in the energy bill are higher compared to previous scenarios (Table 3). The excess electricity represents 2% of the total electricity produced by PV and the micro-CHP units and equal to 106 kWh per year. The micro-CHP unit proposed is smaller than the minimum commercial size available, which is 1 kW, and the resulting poly-generation system is complicated by the four different technologies running together.

The sixth and last scenario takes into account all incentives and a TOU electricity tariff. The model selects a 3.4 kW PV unit, combined to a 4.5 kW HP and a TES with a maximum energy capacity of 13.9 kWh (~860 litres with a difference in the TES water outlet and inlet of 15 degree Celsius). The poly-generation system provides up to 25% and 26% reduction, respectively, in the primary energy and CO_2 emissions. The energy bill is 80% lower than standard energy generation, mainly due to the revenues coming from the supporting schemes for poly-generation. In this case, the electricity exported to the grid reduces to zero. The solution, therefore, avoids the impact of an intermittent renewable energy source (solar PV) on the electricity network. The initial investment is about £11,000, and it is recovered in seven years based on SPB, with a lifespan of poly-generation technologies ranging from fifteen to twenty years.

To better understand the last and best scenario, Figures 6 and 7 show, respectively, how the electrical and thermal energy demand is met by the poly-generation system.

Following the minimisation of the total annual energy cost, the electricity produced by the PV unit (Figure 7) is mainly used to feed the HP. Figure 7 also shows the global horizontal insulation for the typical day of January considered in the analysis.

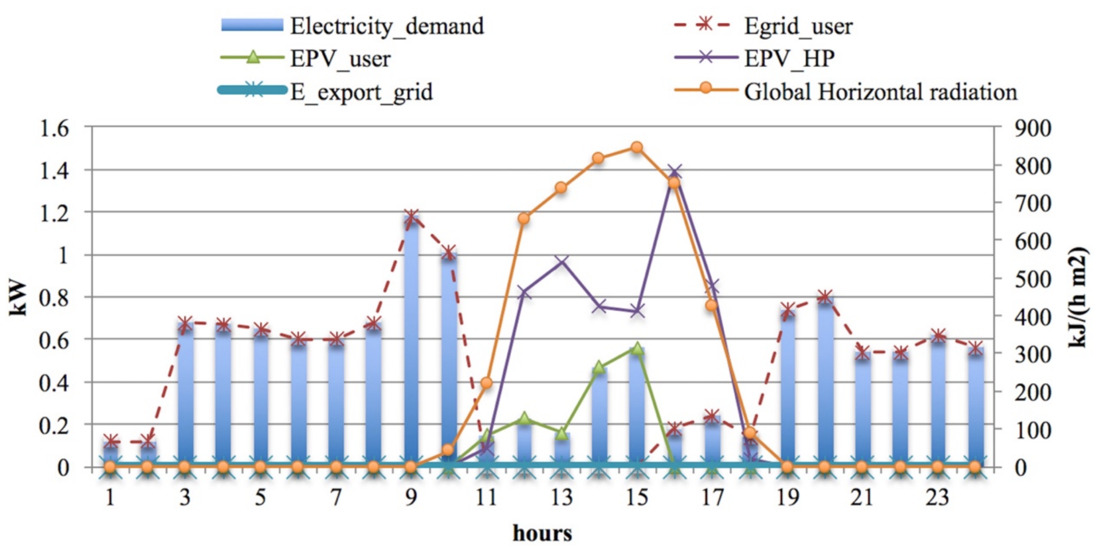

Figure 7. Simulation results of a typical day in January–Electrical outputs, best case scenario

There is no excess electricity exported to the grid. The thermal demand (Figure 8) is partially met by the existing heat boiler, in particular during the peak hours and by the HP either directly or through the TES. The TES reduces the size of the HP, thus reducing the investment cost in poly-generation technologies.

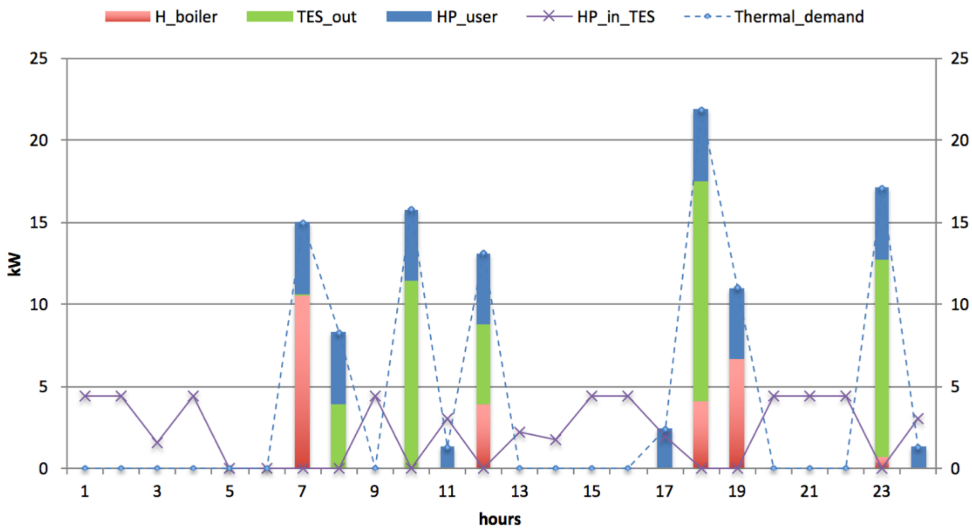

Figure 8. Simulation results of a typical day in January–Thermal outputs, best case scenario

To understand how the solution in the best scenario is influenced by the energy loads considered, a sensitivity analysis was developed, increasing and decreasing the thermal and electrical loads of 15% (Figure 9).

Figure 9 shows that the optimal mix of technologies identified by the model is always the same: a PV unit combined to a HP and coupled to a TES. The size of the PV unit does not change, always limited by the roof space availability. Very small changes can be appreciated in the sizes of the TES and HP, for a variation of the electrical load. A 15% reduction in the electricity demand increases the savings in the energy bill from 80% to 83% compared to standard energy generation. In this case, the PV production is able to cover a higher percentage of the energy demand. In contrast to the previous solution, a 15% increase in the electricity demand reduces the savings in the energy bill. However, the reduction amounts to just 2%.

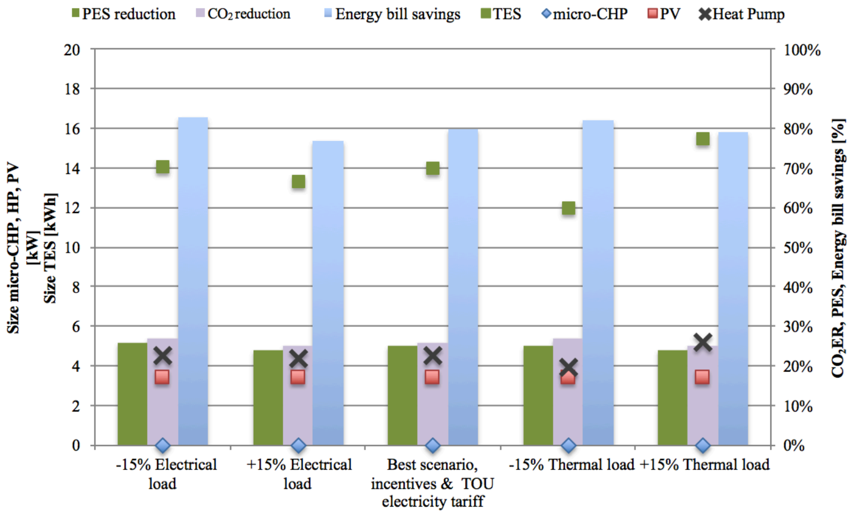

Figure 9. Effect of variation of electricity and thermal load on the best case scenario

A 15% decrease in the thermal demand reduces the size of the TES (from 13.98 kWh to 12 kWh) and HP (from 4.55 kW to 3.9 kW). In this case, the incidence of the thermal energy produced by the HP and fed by the PV unit is bigger, increasing the savings in the energy bill from 80% to 82%. A 15% increase in the thermal demand reduces the economic savings by 1%.

A sensitivity analysis was developed to understand the influence of the natural gas and electricity tariffs on the best scenario. Figure 10 shows the effect of a 15% reduction, and a 15% and a 30% increase in natural gas tariff. A 15% reduction in the natural gas tariff makes using the gas boiler to cover the heat demand more convenient, resulting in a 3% reduction in the energy bill savings with poly-generation. The effect of an increase in the natural gas tariff is opposite. In this case, using electricity to meet the heat demand is more convenient. Therefore, the sizes of the HP and the TES are bigger and the economic saving achievable is greater.

Figure 11 shows the effect of varying the TOU electricity tariff. A 15% decrease in the TOU tariff makes using electricity to meet the heat demand more convenient. The size of the HP is almost the same, with a slight increase in the size of the TES from 13.98 kWh to 15.1 kWh.

The savings in the energy bill increase up to 91%. An increase in the TOU tariff reduces the benefits of the poly-generation. A 30% increase reduces the economic savings from 80% to 64%. However, the poly-generation system is still more convenient than the standard energy generation. The variation in the energy tariff leads to a small variation in the size of the poly-generation technologies, which may increase or decrease by a maximum of 17%.

Therefore, the effect of variable energy tariffs was tested while keeping the size of the poly-generation technologies equal to the ones selected in the best scenario. The results showed that the solution identified in the best scenario can hedge elderly households by an increase in the energy tariff. For a 15% increase in the electricity tariff, the savings in the energy bill slightly reduce from 80% to 73% (Figure 11), and for a 15% increase in the natural gas tariff, the economic savings increase up to 81% (Figure 10).

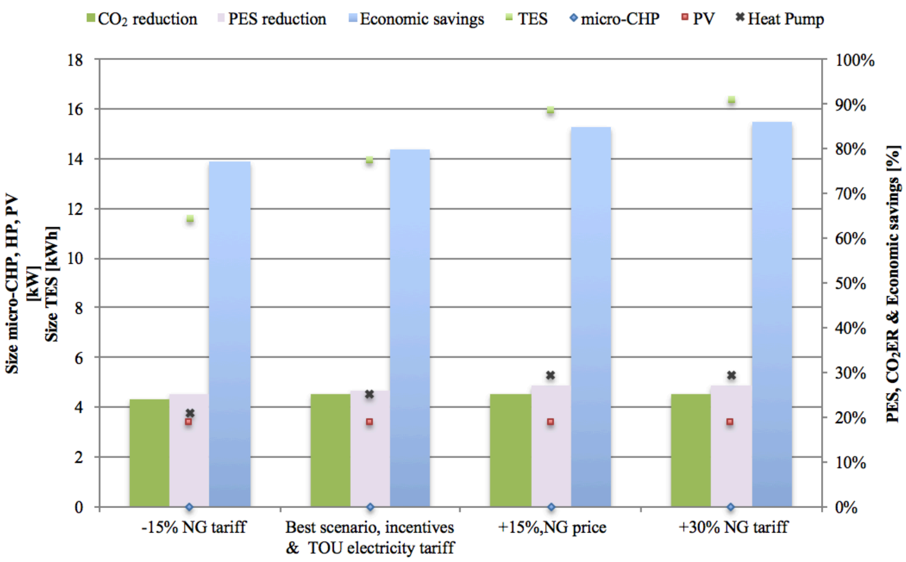

Figure 10. Effect of NG tariff variation on the best case scenario

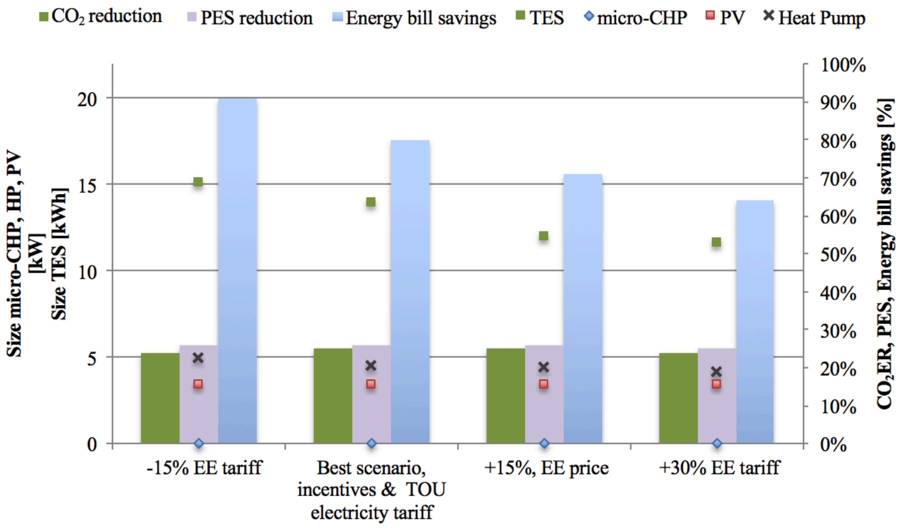

Figure 11. Effect of electricity tariff variation on the best case scenario

5. CONCLUSION

An aging society poses an energy challenge to the built environment already responsible for 40% of CO_2 emissions in the EU [7]. An investigation of the benefits of poly-generation technologies for houses with elderly inhabitants has been carried out.

Results demonstrate that poly-generation is a viable economic solution with government supporting mechanisms, in particular when PV incentive and RHI are available. The incentives considered in the analysis are the ones still available in Northern Ireland for installations completed before February 2016 [49]. Furthermore, such incentives are currently accessible to new installations in Scotland, Wales and England, and in other European countries, like Germany and Italy [46].

For the best case scenario, the merits of poly-generation are: i) 26% CO_2 emission reduction compared to standard energy generation, ii) 80% reduction in the energy bill, iii) no excess electricity from solar production to be exported to the grid, and iv) positive contribution to the management of congestions of the electricity network through the use of a TOU electricity tariff.

The control for the optimal management of poly-generation technologies could be easily incorporated to smart technologies for assisted living that will be necessary to allow elderly people to live at home longer.

PV, HP and TES systems are part of the optimal mix of poly-generation technologies identified in the best case scenario. The retrofit technologies studied can be easily introduced into existing buildings with a minimal intervention and education for elderly people. Micro-CHP units are selected only in case of dedicated supporting mechanisms and always combined with HP and TES systems. In this case, the higher complication of the resulting poly-generation system would not be justified by the increase in the energy and economic savings compared to the best case scenario. Furthermore, in case of a TOU electricity tariff, micro-CHP technologies are not selected by the model. Micro-CHP units, therefore, would not help to solve the problem of congestion of the electricity distribution network. Results also show that the solution identified by the best case scenario is only slightly affected by the variation in the energy tariffs and electrical and thermal demand.

In Northern Ireland, according to [53], the number of household inhabited by elderly people will account to 307,000 by 2037, 79.1% more than 2012. Considering that the test house under analysis represents 28% of the housing stock, it has been assumed that the poly-generation solution studied could, potentially, be applied to 85,960 homes. On the basis of the CO_2 emission reduction achievable by poly-generation technologies, it would be translated in a reduction of 205,400 ton of CO_2 emissions. It means a potential 8% reduction in the emission of the national residential sector by 2037.

The benefits achievable could, therefore, justify the reestablishment or the creation of dedicated supporting mechanisms for poly-generation technologies accessible to elderly people. The impacts of the government energy policy would be: i) 8% reduction in the CO_2 emissions of the residential sector, helping to meet national climate targets, ii) 80% reduction in the energy costs, helping to improve the wellbeing of elderly people living at home and to address the problem of energy poverty and iii) 150 GWh increase in the electricity produced by renewable sources without any additional stress on the electricity distribution network.

The investment required by elderly people is in the range of £11,000, and could be proposed just before the start of the retirement period. The value considered the installation and the Value Added Tax (VAT), which is 5% for energy efficiency and renewable technologies in the UK. Although the pay back in the best scenario is high (7 years), it could be easily repaid within the lifetime of the retrofit technologies, which are characterized by a lifespan ranging from fifteen to twenty years. Elderly people could get advantage of the 77% reduction in the energy bill. Considering that the majority of elderly people in the UK are home-owners, a further possibility to finance the investment in poly-generation technologies could be through reverse mortgage products [54]. In this case, elderly homeowners can borrow money against the value of their property; no payment of the mortgage is required until the borrower dies or the home is sold. Future work will address what happens to the technologies after the elderly person leaves the home, and whether poly-generation technologies could increase the value of the house.

Any additional dedicated incentives to help reduce the initial investment cost could help elderly people in need, allowing them to get advantage of an important reduction of their energy cost.

Even though this study was based on a specific case study in Northern Ireland, results are applicable to other EU countries facing similar challenges. Savings achievable from the use of poly-generation systems would be, in fact, important as shown in the literature [28], although the optimal mix of poly-generation technologies for the specific climate conditions would be different.

It is worth noting that future smart grids could provide information on the half hourly price of energy, making the need to develop a technology selection algorithm as the one described in the present paper even more attracting.

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